Role of Snow Hydrology in Watershed Management

Malchus B. Baker, Jr., Rocky Mountain Research Station, USDA Forest Service, Flagstaff AZ 86001; and
Peter F. Ffolliott, School of Renewable Natural Resources, University of Arizona, Tucson AZ 85721

Abstract

Less than 10% of the annual precipitation in Arizona is recovered for use; most is lost to evapotranspiration. A large portion of the recovered precipitation comes from watersheds in forests at high elevations. Even at these locations, 80% to 85% of the precipitation input is unavailable to downstream users. However, snow accumulates on forested sites throughout the winter and provides a reservoir of water that is potentially available for use in the spring. The possibility of increasing the amount of recoverable precipitation from these watersheds through forest management practices is greater for snow than rain. Snowmelt-runoff forecasting procedures and computer simulation models of snowpack dynamics are available to help hydrologists and watershed managers in this effort.

Introduction

Less than 10% of the annual precipitation in Arizona is recovered for use; most is lost to evapotranspiration. The possibility of increasing the amount of recoverable precipitation from high elevation forested watersheds in Arizona is greater for snow than for rain (Ffolliott et al. 1989, Ffolliott 1993). Snow that accumulates throughout the winter provides a reservoir of water that is potentially available for downstream use in the spring. If snowmelt-runoff volumes were increased significantly, additional water would be available to refill reservoirs or to recharge groundwater aquifers.

Snowpack Conditions

Snowpack conditions in Arizona are often either excessively high or too low in comparison to other regions of the United States. Fluctuations in winter precipitation patterns result in a few wet years interspersed with several average and many below average years (Diaz 1983, Ffolliott et al. 1989). These fluctuations greatly affect the intermittent snowpack buildups on the high-elevation forested watersheds. Intermittent snowpacks, which often disappear between successive storms, vary greatly in their contributions to annual water yields, and to the flow of water to downstream users. Researchers measured snowpack-water equivalents (the amount of liquid water in a snowpack) in the Salt River Basin every March 1st from 1965 to 1985. The results, expressed as a percentage of the average March 1st values, ranged from 13% to more than 25% (Fig. 1), which confirmed the skewness of the snowpack conditions from year to year.

Theoretical and Process Studies

Results from theoretical and process studies allow watershed managers to understand the causal nature of the relationships between snowpack conditions and forest overstories on a watershed better. The effects that forest management practices have on snowpack conditions can often be determined from the results of these studies. The studies also provide a fundamental basis to help explain the results from empirical investigations.

Theoretical studies have centered on synthesis of models to describe short- and long-wave solar radiation exchanges between snowpacks and forest canopies (Bohren and Thorud 1973, Bohren and Barkstrom 1974). The short- and long-wave radiation exchanges vary depending on the existing forest canopy structures. Forest canopies block some short-wave radiation, emit long-wave radiation, and reflect short- and long-wave radiation from the snowpack. Therefore, the effects of manipulating forest overstories on short- and long-wave solar radiation transfers and, as a result, the accumulation and subsequent ablation of snowpacks are predictable.

Researchers have evaluated deposition of intercepted snow in tree canopies with time-lapse imagery to determine the relative significance of snowfall interception in the water budget (Tennyson et al. 1974). Much of the intercepted snow eventually reaches the ground by snowslide, wind erosion, or canopy melt. The potential loss to streamflow by vaporization of canopy snow and resulting snowmelt is small compared with how much snow eventually falls to the snowpack either directly or indirectly from the tree canopies.

Loss of snow from a landscape is due to snowpack melt or to a combination of melting, evaporation, and sublimation. Factors influencing evaporation and sublimation include site characteristics (aspect, slope, etc.), latitude, distance from the ocean, and elevation (Avery et al. 1992). Sublimation rates are higher for the northerly sites, inland sites, and for those at high elevations. Snow cover

Baker, Jr., M. B., and P. F. Ffolliott. 2003. Role of snow hydrology in watershed management. *Journal of the Arizona-Nevada Academy of Science* 35(1):42-47.

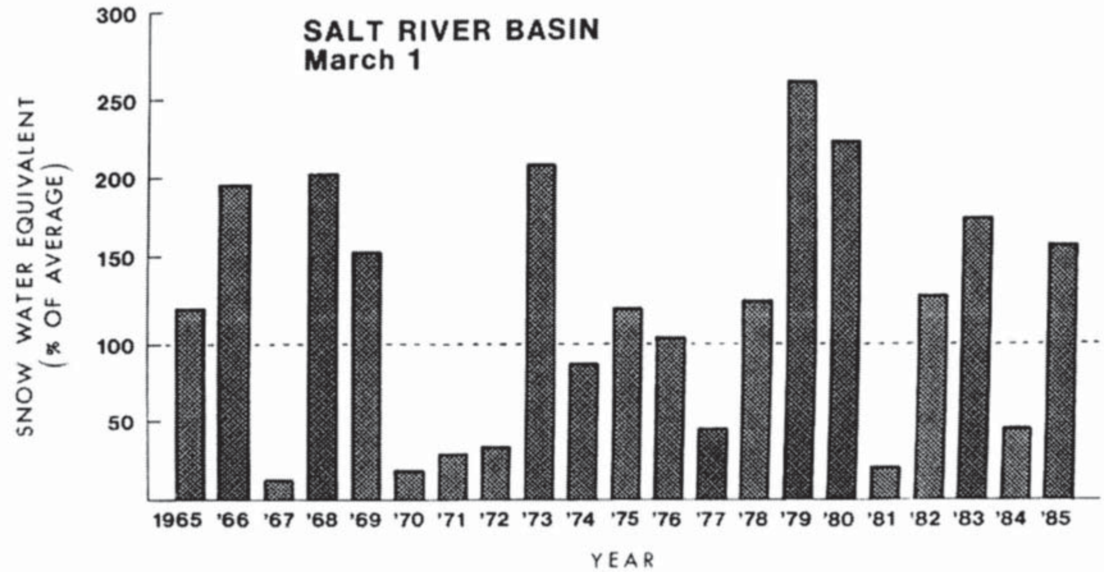

Figure 1. *Snowpack-water equivalents in the Salt River Basin expressed as a percentage of the average March 1st values recorded from1965 to 1985 (from Jones and Brazel 1986).*

losses as little as 25% and as much as 70% are due to melting alone or to a combination of melting, evaporation, and sublimation.

Forest Management Practices

Forest management practices to increase recoverable water yields from snow include forest thinning (reducing forest densities), forest clearing (removing forest overstories), and combinations of the two operations. However, varying intensities of forest thinning and arrangements, sizes, and patterns of forest clearings are possible. Snow research in Arizona has focused on effects of thinning and clearing forest overstories on snowpack accumulation and melt patterns.

Forest Thinning

Inventory-prediction relationships describing snowpack conditions within the high-elevation forests from readily available or easily obtainable input data show that snowpack-water equivalents generally increase as forest densities decrease (Ffolliott et al. 1989, Ffolliott 1993). With these inventory-prediction relationships, watershed managers can prescribe thinning practices to increase snowpack-water equivalents on-site, which will convert into recoverable water.

Storage-duration values obtained by adding snowpack-water equivalent measurements from successive sampling dates (Wilm 1948, Warren and Ffolliott 1975) provide information on the temporal variabilities of the relationship between snowpack conditions and forest characteristics. Maximum values show high initial storage and slow melt, while minimum values show low initial storage and rapid melt. Studies have shown that maximum storage-duration values are associated with low forest densities, cool sites, and high elevations, while minimum storage-duration values are associated with high forest densities, warm sites, and low elevations. A watershed manager can partially modify the storage-duration of a snowpack through forest management activities.

Forest Clearing

Greater accumulations of snow for possible conversion into recoverable water are available in cleared openings rather than under forest canopies. The greatest accumulations of snow are in cleared strips and patches with less than 1½ H (H = average height of adjacent trees) in size (Ffolliott et al. 1989, Ffolliott 1993). While clearing forest overstories affects snowfall accumulation and melt patterns, the amount of snow that falls onto the watershed remains unchanged. Increased snow in the openings is partially associated with a reduction in snowpack accumulations in the adjacent forest.

Techniques to evaluate snowpack profiles in and adjacent to forest openings include a two-dimensional analytical method of estimating where an increase or decrease in snowpack-water equivalents occurs based on the openings at a point in time (Fig. 2). The tradeoff between changes in the snowpack and the volumes of forest overstory cleared to create the openings can be identified using this method (Ffolliott and Thorud 1974, Ffolliott et al. 1989). Further investigations led to a series of three-dimensional time-space models that describe the snowpack conditions in and adjacent to openings based on the volumetric content of water (Ffolliott 1983). Information from these models can be helpful to managers when increased water yields from snowpacks are a watershed management objective.

RUNOFF EFFICIENCIES

A measure of the effects of physiographical and climatological factors on the quantity of snowmelt runoff from a watershed is *runoff efficiency*, which is the portion of a snowpack's water equivalent converted into surface runoff (Ffolliott and Hansen 1968, Thorud and Ffolliott 1972). Both fixed and variable factors of a site influence the runoff-efficiency value of a watershed. Fixedfactors include slope percent, aspect, soil type and depth, and watershed configuration. Among the variable factors are year-to-year differences in the rates of snowmelt on the watershed and preceding soil moisture conditions. Depending largely on the amount and timing of the snowfall, runoff efficiencies from peak seasonal accumulation to the cessation of snowmelt runoff can range from 20% to 45%. Runoff efficiencies vary from 25% to almost 90% among watersheds in a particular year, with much of this difference attributed to physiographic features.

Researchers have developed equations that predict runoff efficiency from variables measured before peak seasonal snowpack accumulation and during the snowmelt-runoff regime (Solomon et al. 1975). Equations for predicting runoff efficiency from inventory-prediction measurements before peak seasonal snowpack accumulation can be used to estimate the portion of a snowpack that might be converted into runoff in a season. Other equations that estimate runoff efficiency after the end of a season's snowmelt-runoff period are used to characterize a watershed on based past runoff efficiency history and water-yielding potentials. Watersheds with the greatest peak seasonal snowpack accumulations and at the highest elevations generally have the most efficient snowmelt-runoff regimes. Consequently, forest management activities implemented to increase snowpack-water equivalents at peak seasonal accumulation have the greatest potential for snowmelt-runoff improvement.

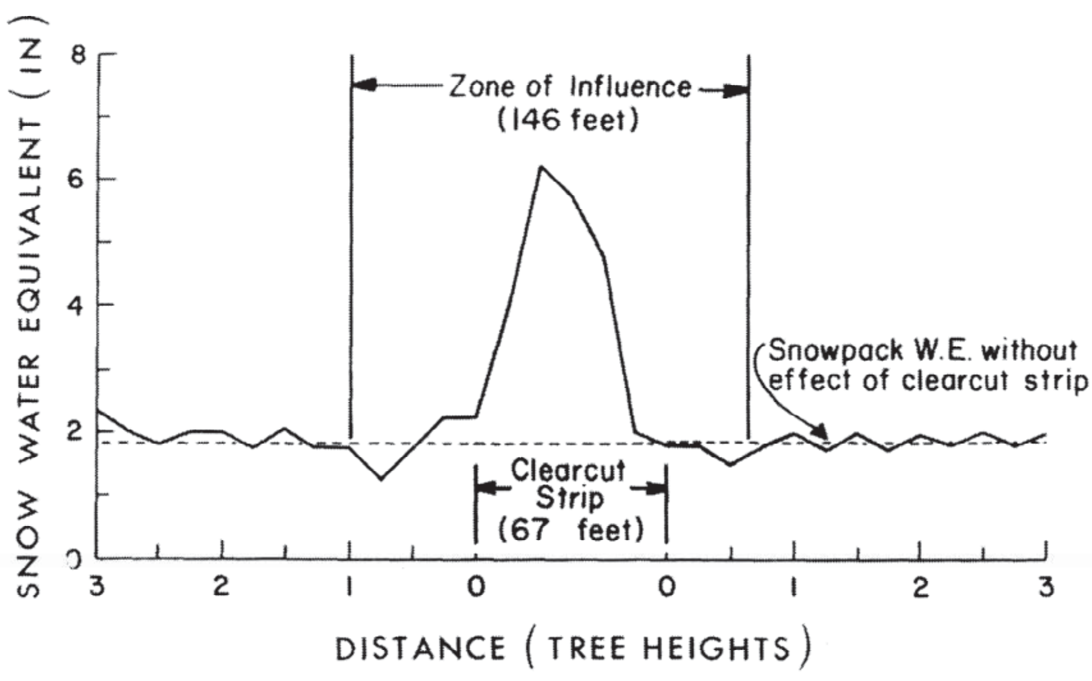

Figure 2. Snowpack profile in clearcut strips at peak seasonal accumulation, with the zone of influence delineated (from Ffolliott and Thorud 1974). The effect of the clearcut strip was a net increase in the water equivalent of the snowpack.

SNOW CHEMISTRY

Water contained in Arizona's snowpacks is high in chemical quality—the concentrations of K, Na, Ca, Mg, F, Cl, NO_3, and SO_4 are low and little evidence of higher than typical concentrations of these chemicals exists (Ffolliott and Lopes 1993). Concentrations of these chemicals in snowmelt-runoff water are also relatively low and have always been less than the water quality criteria established by the U.S. Environmental Protection Agency (1980) and the Arizona Department of Environmental Quality for aquatic life, irrigation, and public water supplies (Ffolliott 1990). However, the link between the chemicals in snowpacks and those in subsequent snowmelt runoff is unknown.

There is also little evidence of high pH values in the snowpacks. This finding is expected, however, because of the low concentrations of sources for atmospheric pollutants and local contamination.

REMOTE SENSING OF SNOWPACK CONDITIONS

Intensive inventories of snowpack conditions are uneconomical. However, estimating snowpack conditions indirectly from measurements obtained through remote-sensing techniques is an alternative. Relating peak seasonal snowpack accumulation and topographic attributes measured on standard 1:15,840 black-and-white aerial photographs to forest overstory is possible (Larson et al. 1974). As mentioned, knowledge of peak seasonal snowpack accumulation is important to estimate the potential snowmelt-runoff volumes from Arizona's watersheds.

Measures of snowpack depletion are highly correlated with the volume of snowmelt runoff. Because the snowpacks in Arizona are shallow and intermittent in contrast to conditions in other regions, measures of snowpack depletion are also related to the extent of snow cover. To evaluate the hypothesis that future runoff regimes can be estimated based on snow-cover data from satellite imagery, researchers measured snow cover from LANDSAT imagery and compared the results to subsequent snowmelt-runoff volumes during snowpack depletion periods (Aul and Ffolliott 1975, Ffolliott and Rasmussen 1976). Anticipated snowmelt-runoff regimes can be forecast from these relationships.

SIMULATION MODELS

Snowpack conditions at a point-in-time reflect the combined effects of accumulation, redistribution, and melt processes that occurred before that point-in-time. Simulation models are available to help separate the complexities of these processes, and allow managers to conduct forest management activities that manipulate snowpack conditions in a hydrologically favorable manner. These simulators are useful to quantify on-site snowpack accumulation, redistribution, and melt processes within a dynamic framework (Ffolliott and Rasmussen 1979). The input data needed to run the simulation models are readily available.

Knowing the contributions of the melting snowpacks to streamflow regimes from high-elevation watersheds is also necessary. Modification of a snowmelt simulation model for Colorado subalpine forests provides predictions of the contributions of the relatively shallow and intermittent snowpacks in Arizona to streamflow. This generalized model requires only limited knowledge of watershed condition and snowpack parameters (Solomon et al. 1976). The driving variables in the simulator are daily values of maximum and minimum air temperatures, precipitation amounts, and imposing shortwave radiation loads. Verification of the simulation model on watersheds representing a range of conditions common to high elevation, forested watersheds in Arizona has been satisfactory. Interrogations of the model provides information on watershed conditions that are most favorable to increased snowmelt-runoff volumes.

MANAGEMENT IMPLICATIONS

Forest management practices increase annual water yields from selected watersheds in Arizona's mountains (Ffolliott et al. 1989, Ffolliott 1993, Ffolliott and Baker 2000). Larger increases occur in wet years, when the soil mantle has been recharged before snowmelt began. Little or no increase in snowmelt-runoff volume occurs in dry years, when most of the snowmelt-runoff recharges the soil mantle. The duration of the changes in annual snowmelt-runoff volumes attributed to forest management practices implemented on upland watersheds largely depends on the condition of the watersheds both before and after the forest management practices are implemented. The changes are likely to diminish in 10 years or less to the levels of streamflow observed before the forest management practices were implemented (Baker 1999).

Debate also exists about what portion of the streamflow increases that are being attributed to forest management practices contribute to downstream water supplies. Brown and Fogel (1987) suggest that this portion is relatively small in the Salt and Verde Rivers because of transmission losses, evaporation, seepage, and reservoir spills. Simulations of water routing with and without implementation of forest management practices by these authors showed that less than half the streamflow increase is likely to reach downstream users.

SUMMARY

Theoretical and process studies, empirical field observations, and simulation investigations provide a basis for the development of management practices to enhance snowmelt runoff on high-elevation forested watersheds in Arizona. Forest management practices can be designed to increase the amount of recoverable water from melting snowpacks on watersheds with high-runoff efficiencies. These management practices can also furnish livestock and wildlife forage, wildlife habitats, and amenity values in combinations that the people in Arizona will need into the coming century.

However, the issue of whether forest management practices can or will ever be implemented to alter snowpack dynamics is unresolved. The emphasis of watershed management in Arizona has changed from a focus on increasing water supplies to a more holistic perspective of natural resource management (Baker 1999). Current watershed management considers other ecosystem-based, multiple-use values of watershed lands including forage, wildlife, and recreational use. These critical values have been identified through society's expressions about the future management of watersheds and natural resources.

LITERATURE CITED

AUL, J. S., and P. F. FFOLLIOTT. 1975. Measuring snow cover from ERTS's imagery on the Black River Basin. *Hydrology and Water Resources in Arizona and the Southwest* 5:215-219.

AVERY, C. C., L. R. DEXTER, R. R. WIER, W. G. DELINGER, A. TECLE, and R. J. BECKER. 1992. Where has all the snow gone? Snowpack sublimation in northern Arizona. *Western Snow Conference* 60:84-94.

BAKER, JR., M. B., compl. 1999. *History of watershed research in the central Arizona highlands*. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-29, Fort Collins, CO.

BOHREN, C. F., and B. R. BARKSTROM. 1974. Theory of optical properties on snow. *Journal of Geophysical Research* 79:4527-4535.

BOHREN, C. F., and D. B. THORUD. 1973. Two theoretical models of radiation heat transfer between forest trees and snowpacks. *Agricultural Meteorology* 22:3-16.

BROWN T. C., and M. M. FOGEL. 1987. Use of streamflow increases from vegetative management in the Verde River. *Water Resources Bulletin* 23:1149-1160.

DIAZ, H. F. 1983. Some aspects of major dry and wet periods in the contiguous United States, 1895-1981. *Journal of Climatology and Applied Meteorology* 22:3-16.

ENVIRONMENTAL PROTECTION AGENCY. 1980. Office of Research and Development, Environmental Protection Agency. EPA-600/979036, Washington, DC.

FFOLLIOTT, P. F. 1983. Time-space effects of openings in Arizona forests on snowpacks. *Hydrology and Water Resources in Arizona and the Southwest* 13:17-20.

FFOLLIOTT, P. F. 1990. Water quality of streamflow from selected forested watersheds in Arizona. *Hydrology and Water Resources in Arizona and the Southwest* 19:1-5.

FFOLLIOTT, P. F. 1993. Snowpack dynamics in mountain areas: Research findings in the southwestern United States. Pp. 129-139 *in* S. Chandra, tech. coord., *International symposium of mountainous areas*. Shimla, India.

FFOLLIOTT, P. F., and M. B. BAKER, JR. 2000. Snowpack hydrology in the southwestern United States: Contributions to watershed management. Pp. 274-276 *in* P. F. Ffolliott, M. B. Baker, Jr., C. B. Edminster, M. C. Dillon, and K. L. Mora, tech. coords., *Land stewardship in the 21st century: The contributions of watershed management*. USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-13, Fort Collins, CO.

FFOLLIOTT, P. F., G. J. GOTTFRIED, and M. B. BAKER, JR. 1989. Water yield from forest snowpack management: Research findings in Arizona and New Mexico. *Water Resources Research* 25:1999-2007.

FFOLLIOTT, P. F., and E. A. HANSEN. 1968. *Observations of snowpack accumulation, melt, and runoff on a small Arizona watershed.* USDA Forest Service, Rocky Mountain Research Station, Research Note RM-124, Fort Collins, CO.

FFOLLIOTT, P. F., and V. L. LOPES. 1993. Acidity and chemistry of Arizona's snowpacks. Pp. 305-310 *in* R. G. Allen and C. M. U. Neale, eds., *Management of irrigation and drainage systems: Integrated perspectives*. 1993 National Conference on Irrigation and Drainage Engineering, American Society of Civil Engineers, New York.

FFOLLIOTT, P. F., and W. O. RASMUSSEN. 1976. Use of satellite data to develop snowmelt-runoff forecasts in Arizona. *Hydrology and Water Resources in Arizona and the Southwest* 6:149-151.

FFOLLIOTT, P. F., and W. O. RASMUSSEN. 1979. An interactive model of snowpack accumulation and melt dynamics in forested conditions. Pp. 359-368 in S. C. Colbeck and M. Ray, eds., *Modeling of snow cover runoff.* U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

FFOLLIOTT, P. F., and D. B. THORUD. 1974. A technique to evaluate snowpack profiles in and adjacent to forest openings. *Hydrology and Water Resources in Arizona and the Southwest* 4:10-17.

JONES, R., AND A. J. BRAZEL. 1986. Problems associated with the variability of Southwest precipitation and seasonal snowpacks. *Western Snow Conference* 54:12-17.

LARSON, F. R., P. F. FFOLLIOTT, and K. E. MOESSNER. 1974. *Using aerial measurements of forest overstory and topography to estimate peak snowpack.* USDA Forest Service, Rocky Mountain Research Station, Research Note RM-267, Fort Collins, CO.

SOLOMON, R. M., P. F. FFOLLIOTT, M. B. BAKER, JR., G. J. GOTTFRIED, and J. R. THOMPSON.1975. *Snowmelt runoff efficiencies in Arizona watersheds.* Arizona Agricultural Experiment Station, Research Paper 274, Tucson.

SOLOMON, R. M., P. F. FFOLLIOTT, M. B. BAKER, JR., and J. R. THOMPSON. 1976. *Computer simulation of snowmelt.* USDA Forest Service, Research Paper RM-174, Fort Collins, CO.

TENNYSON, L. C., P. F. FFOLLIOTT, and D. B. THORUD. 1974. Use of time-lapse photography to assess potential interception in Arizona ponderosa pine. *Water Resources Bulletin* 10:1246-1254.

THORUD, D. B., and P. F. FFOLLIOTT. 1972. Development of management guidelines for increasing snowpack water yields from ponderosa pine forests in Arizona. Pp. 171-173 in *Watershed in transition.* American Water Resources Association, Fort Collins, CO.

WARREN, M. A., and P. F. FFOLLIOTT. 1975. Describing snowpacks in Arizona mixed conifer forests with a storage-duration index. *Hydrology and Water Resources in Arizona and the Southwest* 5:87-89.

WILM, H. G. 1948. The influence of forest cover on snow melt. *Transactions of the American Geophysical Union* 29:547-556.